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Physics and Advanced Technologies LDRD Final Report:Adaptive Optics Imaging and Spectroscopy of the Solar System

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Physics and Advanced Technologies LDRD Final Report
Exploratory Research Proposal

ADAPTIVE OPTICS IMAGING AND SPECTROSCOPY OF THE SOLAR SYSTEM

#01-ERD-013

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1 Introduction

This focus of this project was the investigation of the planets Uranus and Neptune and Saturn's moon Titan using adaptive optics imaging and spectroscopy at the 10-meter W.M. Keck Telescopes. These bodies share a common type of atmosphere, one that is rich in methane and has a hydrocarbon haze layer produced by methane photolysis. Neptune and Uranus have atmospheric features which change on short timescales; we have investigated their altitude, composition, and connection to events occuring deeper in the planets' tropospheres. Titan has a solid surface located under its atmosphere, the composition of which is still quite uncertain. With spectra that sample the vertical structure of the atmosphere and narrowband observations that selectively probe Titan's surface we have determined the surface reflectivity of Titan at near-infrared wavelengths.

The Keck Observatory adaptive optics (AO) system allows us to image solar system bodies at a spatial resolution that is at least 10 times better than conventional imaging without adaptive optics. Spectroscopy is also available in combination with the AO system, which has allowed us to obtain spectra of individual features on the disks of distant solar system objects. Our collaborator Prof. Imke de Pater (UC Berkeley) and her graduate students Henry Roe and Shuleen Martin have been extensively involved with the modeling of this data to determine the atmospheric and surface properties of Neptune, Uranus, and Titan.

2 Background

2.1 Adaptive Optics Observations

Adaptive optics (AO) is a technique of compensating for atmospheric seeing conditions by actively correcting the phase of the incoming light. Compensation is accomplished by sensing the incoming 'reference source' wavefront (which should be flat in the absence of an atmosphere) using a wavefront sensor, and imposing the negative of the sensed wavefront on a deformable mirror. This correction of the atmospheric distortion is equally valid for the science object provided the reference source is nearby. The reference source used must be relatively bright to produce enough photons for wavefront analysis. This is problematic for observations of dim sources, since only about 1% of the sky has a bright star near enough to serve as a reference source. However, since the reference object does not have to be a point source, a bright planet or satellite can also serve as a reference source for itself and nearby objects. Uranus, Neptune, and Titan are excellent targets for adaptive optics since they are bright enough to serve as wavefront reference sources for themselves.

A new infrared camera, NIRC2, was installed at Keck in 2002. Unlike the earlier interim cameras used with the AO system, NIRC2 was specifically designed for high-resolution imaging. It has a larger field of view than previous interim cameras, 10 arcseconds rather than 5, and a pixel scale of 0.01 arcseconds. This makes it possible to produce spectacular images such as the image of Uranus and its ring system (Fig. 1) in a single exposure.

2.2 Spectroscopy

The Keck Telescope is equipped with NIRSPEC, a near-infrared spectrometer operating at 1-5 μm. NIRSPEC can be used to take low-spatial-resolution spectra of planetary bodies in order to obtain good signal-to-noise in a reasonable amount of observing time, or it can be used behind the adaptive optics system to obtain spatially-resolved spectra; that is, to obtain spectra for individual features on the planetary disk. Such a capability offers obvious advantages for bodies such as Neptune and Titan, which have distinct features at scales too small to be resolved by conventional (non-AO) spectroscopy. We have obtained both AO and non-AO NIRSPEC spectra of Neptune, Uranus, and Titan.

An exciting development in 2002 was the advent of the NIRC2 camera with its associated spectrograph. The NIRC2 spectrograph provides data at a much better signal to noise ratio than NIRSPEC (fig. 2). In both 2002 and 2003 we obtained NIRSPEC spectra of Neptune and Titan (discussed below).

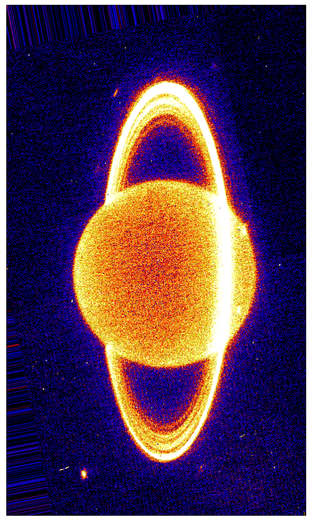


Figure 1: Near-infrared (2μm) image of Uranus taken on 2 August 2002. This image clearly shows the individual rings of Uranus, which have never before been resolved by an Earthbased telescope.

2.3 Atmospheric Modeling

The goal of this project is to obtain quantitative information from the impressive images and spectra of the planets produced by adaptive optics. For this purpose it is necessary to model the atmospheres of these bodies in some detail. We have worked with two different atmospheric models, one that we used to calculate radiative transfer in Neptune's atmosphere (developed by former UC Berkeley graduate student Henry Roe, now at Caltech), and a model developed by our NASA collaborators Chris McKay and Eliot Young, which calculates radiative transfer in Titan's atmosphere. We also completed preliminary calculations on a 3-D radiative transfer model using a LLNL-developed code, ARDRA, which showed that this code has much promise for planets and satellites such as Titan, which has an atmosphere large compared to the size of the satellite.

3 Accomplishments of the Project

3.1 Neptune

Neptune has a very dynamically-active atmosphere, with high winds and infrared-bright 'storm' features that appear in bands north and south of the planet's equator (Fig. 2). Neptune's storm systems are highly variable over time, with time scales reported between hours and years. We have been investigated both the dynamics of Neptune's cloud features and the structure of Neptune's atmosphere using adaptive optics images and spectroscopy.

The research described below has been a joint effort carried out by UC Berkeley graduate student Shuleen Martin (as part of her Ph.D. thesis; Martin has been supported by an IGPP minigrant), LLNL researcher Seran Gibbard, and UC Berkeley Professor Imke de Pater, in collaboration with Bruce Macintosh and Claire Max. Over the past few years we have acquired a large body of images and spectra of the planet Neptune from the W.M. Keck Telescope using the Adaptive Optics (AO) system. Our first datasets were taken in June 2000, with a few isolated images in 1999/2000 during Keck AO engineering runs. The AO engineering images were published by Max *et al.* (2003).

AO images of Neptune at near-infrared wavelengths are characterized by bright features due to scattering of solar radiation by hydrocarbon hazes and clouds in the upper troposphere and stratosphere, against a disk that is dark due to absorption by methane and molecular hydrogen (fig. 2). Negative contrast features, such as the famous Great Dark Spot (GDS) cannot be detected directly at these wavelengths. However, the high spatial resolution afforded by AO (typically $\sim$ 0.05-0.07 arcsecond, or about 35-40 resolution elements across the disk of Neptune) enables the study of cloud morphology and motions which may imply the presence of dynamic structures such as vortices.

Clouds are concentrated in a thin band near 35° N and in a wide band $20-50°$ S. These cloud bands often contain bright "storm" features. We obtained spectra of these features on June 16-17 2000 using the NIRSPEC spectrograph coupled with the AO system, and on August 2-3 2002 using the NIRC2 camera and spectrograph. An example of such a spatially-resolved spectrum is shown in figure 2. Using a radiative transfer model developed by graduate student Henry Roe under an IGPP minigrant (Roe et al. 2001; *Astron. J.*, **122**, 1023-1029), we determined the altitude at which the bright features are located, and hence obtained a three-dimensional 'picture' of the planet's upper troposphere and stratosphere. We detected a distinct difference between Neptune's southern and northern hemisphere. The northern features ($30-45°$ N. latitude) are found highest in the atmosphere, at 0.02-0.06 bar, i.e., in Neptune's stratosphere. Southern features (-30 to $-50°$ S. latitude) are located in the upper troposphere (0.10-0.14 bar), near the tropopause, while the small features at $-70°$ S. are deeper in the troposphere, near 0.2-0.3 bar. This result suggests the existence of large scale dynamical motions, such as a Hadley cell circulation. These results have been published by Gibbard *et al.* (2003).

Our ability to resolve the detailed morphology of the cloud bands on Neptune provides a unique opportunity to study the temporal and spatial changes in the bands. During a typical observing sequence, we integrate for only 1 minute per image (since Neptune rotates in only 16 hours, longer integrations would blur the feautres); hence the number of images per night is high. Because the amount of detail visible in each image is also large, there is a tremendous amount of information available that can be used to characterize features and to determine changes in their morphology over time, their flow speeds, and exact motion.

In her studies of minute-by-minutes changes in the morphology of Neptune's cloud bands, graduate student Shuleen Martin has found evidence that features are diverted around infrared-dark oval-shaped regions. Furthermore, the motions of small cloud features that make up these bright bands do not, in general, follow the wind profile as determined by Voyager. In fact, velocities are not constant, but rather increase and decrease near these infrared-dark features. The complete characterization of these small cloud motions is not yet complete, but preliminary results indicate that infrared-dark regions may be vortices.

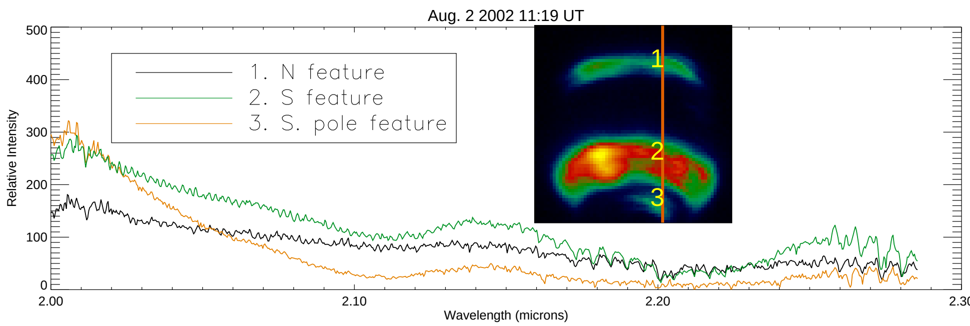
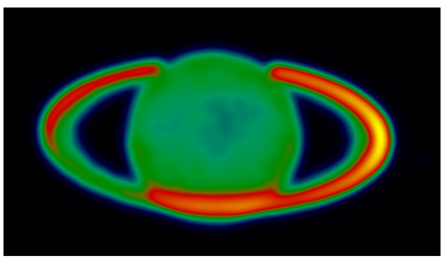


Figure 2: K-band spectra of Neptune obtained on 2 August 2002 with the NIRC2 spectrograph in combination with the Keck adaptive optics system (from Gibbard *et al.* 2003). Spectra are shown for three features seen in the inset image: a northern feature, a southern feature, and a smaller feature further south. The different shapes of the spectra indicate that the features are located at different altitudes in the planet's atmosphere.

3.2 Uranus

Unlike Neptune, Uranus does not have dramatic time-varying features on its disk. It has an internal heat source at least ten times smaller than Neptune's, and its atmosphere shows much less activity than Neptune's (Gautier *et al.* 1995). These two facts are probably related, although the details of the connection between the planet's internal structure and its atmosphere are unknown. Uranus does show some time-varying atmospheric features (Karkoschka and Tomasko 1998, Allison *et al.* 1991), but their size and contrast is much less than is seen for Neptune.

Uranus has a complicated ring structure which appears bright in the infrared. Groundbased astronomy using conventional techniques cannot resolve the ring structure; however with adaptive optics at the Keck Telescope we have done so (figs. 1,3). Determining the brightness of individual rings gives us information on the ring particle properties such as size and composition; we can also learn about ring dynamics by studying azimuthal variations due to gravitational interactions with Uranus' moons.



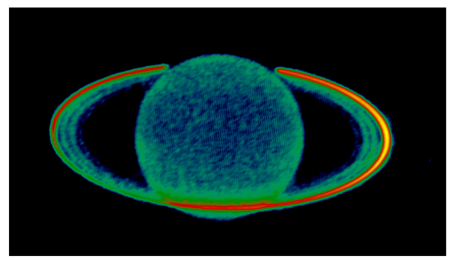


Figure 3: Images of Uranus as it appears without adaptive optics (conventional image, left) and with AO (right)

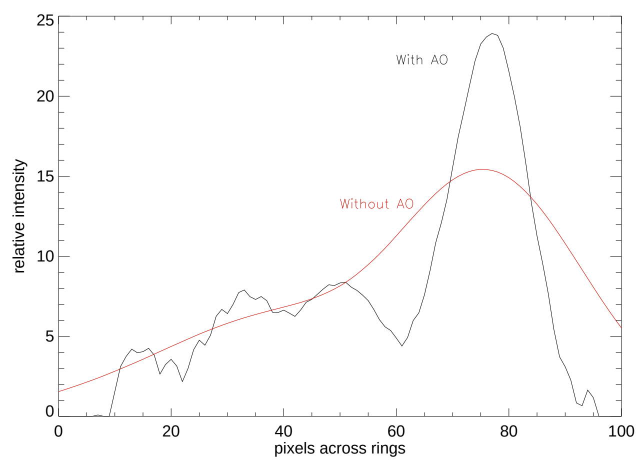


Figure 4: Uranus ring profile (a 'slice' through the rings) of images shown above. In the non-AO case only the bright epsilon ring can be seen; with AO it is possible to resolve not only the groups of rings (large bumps) but also individual ringlets (small ripples)

Images of Uranus obtained in 2000 and 2001 clearly demonstrated the superiority of adaptive optics over conventional infrared imaging. Not only were we able to determine rotation periods for 8 separate infrared-bright features; we were also able to obtain spectacular images of the Uranian ring system (de Pater *et al.* 2002). Even more spectacular images were obtained with the new near-infrared camera NIRC2 in August 2002. In these images we resolved individual rings (not possible even with the Hubble Space Telescope). These images will enable us to obtain individual ring albedoes and investigate the north/south brightness ratio of the bright ϵ ring, which is sensitive to the structure of that ring.

3.3 Titan

Saturn's large moon Titan is the only planetary satellite surrounded by a thick atmosphere. This atmosphere consists primarily of nitrogen gas, with a few percent methane. Photodissociation of methane in the stratosphere is followed by a complex series of reactions that produce ethane, complex heavier hydrocarbons, and haze particles made of large molecules resembling polymers. Although Titan's atmosphere is opaque to visible light, Titan's surface can be probed in the infrared through narrow spectral windows between methane absorption bands. The presence of a thick atmosphere, large quantities of organic compounds, and possible liquid reservoirs on the surface makes Titan a natural laboratory for studies of the primitive Earth at the time life began. With this in mind, NASA is sending the Huygens probe to descend through Titan's atmosphere in 2004 as part of the Cassini mission to Saturn.

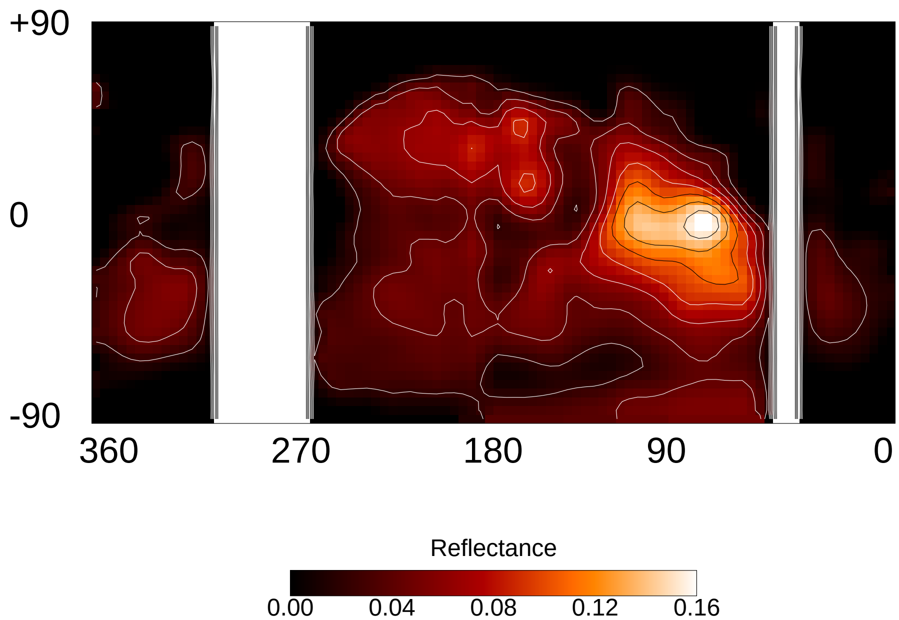


Figure 5: Surface albedo map of Titan constructed from adaptive optics observations at a wavelength of 2 microns. The scale shows the fraction of incident light that is reflected from the surface. Blank areas are where no data have yet been obtained.

Our work during this project has focused on both Titan's surface and atmosphere. Our broadband AO observations of Titan, using a 1-D radiative transfer model to separate the contributions of light from Titan's atmosphere and its surface, have led to a high-spatial-resolution surface albedo map of Titan (Gibbard *et al.* 2003). We have also observed Titan in narrowband filters that probe atmosphere and surface separately (Roe *et al.* 2002). We have also obtained spatially-resolved spectra of Titan, which will give us valuable information about the seasonal distribution of haze in Titan's atmosphere and its variation in time.

The accuracy of our 1-D radiative transfer models is limited by the fact that they are least accurate near the limb of Titan (at high angles of incidence). Since the shape of the limb profile provides one of the major constraints in our atmospheric modeling, clearly there is a need for a model that can reproduce the limb shape accurately. We have done preliminary calculations on the feasibility of the use of a 3-D radiative transfer code, ARDRA, developed at LLNL. As an initial test of the applicability of the ARDRA model, a simple planetary model using a single light element atmosphere and a heavy element planet was used together with a highly displaced point source radiation field (provides an incident plane wave on the planet) to examine the scattered radiation field and the actinic flux in the atmosphere. Preliminary results indicate that the ARDRA code can be successfully adapted to produce an accurate representation of the flux from Titan.

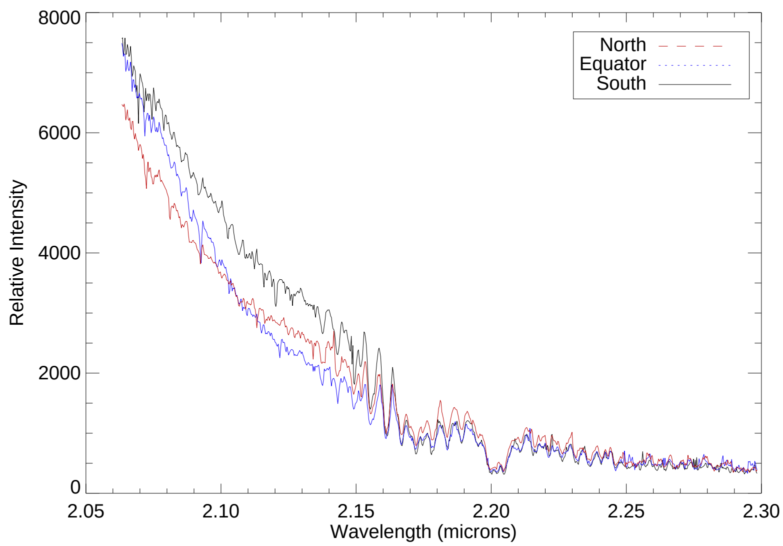


Figure 6: Spectra of Titan taken using NIRSPEC with the adaptive optics system. The spectra are spatially resolved, so that the features of the northern hemisphere of the planet can be distinguished from the equatorial region and the southern hemisphere. Portions of this spectra probe different depths in the atmosphere from the upper atmosphere down to the surface. Modeling of this data will enable us to determine the 3-dimensional structure of Titan's atmosphere.

4 Return to the Laboratory

The return to the laboratory for this project will be considerable in terms of favorable publicity. Our observations of Neptune and Titan have resulted in considerable press coverage, including our Neptune image on the cover of Science News as well as prominent articles in Science, Nature, Sky and Telescope, and Astronomy magazine, and on the websites of CNN and the BBC. High-visibility planetary astronomy projects at LLNL have the potential to recruit young scientists interested in working at the forefront of technology and modeling capability. Drawing together researchers from several different disciplines including planetary science, atmosphere modeling, adaptive optics, image processing and information science and technologies, this project truly represents the best of cutting-edge science at LLNL.

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